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DESIGN OF A FAST-PLATE GENERATOR DRIVING PLASMA FLOW SWITCH*

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INTRODUCTION

Over the last fifteen years, there has been continuing interest in the use of magnetic flux compression generators to drive plasma implosion loads[1-3]. Studies of fast plate-type generators coupled to cylindrical foil-plasma discharges in z-pinch geometry indicated that operation in the few microsecond time regime (generator time ≈ implosion time) might be successful[3]. Later experiments and two-dimensional MHD calculations demonstrated that penetration of the effects of cold, nonmoving boundaries into the plasma implosion, combined with Rayleigh-Taylor instability, prevents practical attainment of microsecond implosions of cylindrical plasmas (a few cm or less in axial extent). Use of longer plasmas and/or shorter implosion times, however, implies higher effective driving voltages and shorter current risetimes at the load. Since explosively-driven plate generators may already represent the limit of generator performance in terms of speed, it is therefore necessary to include an intermediate stage of power conditioning between microsecond generators and submicrosecond implosion loads. The present paper discusses coupling the plasma flow switch[4,5] to a fast plate generator in order to accumulate magnetic energy in vacuum on a few microsecond timescale and then release this energy rapidly to a submicrosecond implosion load.

SYSTEM ANALYSIS

To examine the system behavior of a fast-plate generator driving a plasma flow switch/inductive store, it is useful to employ a simple lumped-circuit model. Such a model can indicate the relationships between generator and switch parameters and suggest reasonable combinations of circuit values to achieve attractive experimental tests. For the present discussion, the model will further idealize system operation by assuming constant series resistance, constant plasma mass, and simple, linear relationships of inductance with displacement for both the generator and plasma gun.

The circuit current is given by:

$$\frac{d}{dt}\left[(L_g + L_m + L_t + L_s)J\right] = -RJ$$

where J is the circuit current, L_g and L_s are the inductances of the generator and switch, respectively, as swept by their moving conductors,

L_m is the minimum (residual) inductance of the generator, and L_t is the inductance between the generator and initial switch plasma position. The generator and switch inductances are written as:

$$L_g = F_g\, h \quad , \; L_s = F_s\, x$$

where h is the generator plate gap and x is the plasma displacement. With the same constant inductance gradients, the generator (negative) impedance is $Z_g = F_g u_g$ and the switch dynamic impedance is $Z_s = F_s u_s$, where u_g and u_s are the plate closure and switch plasma speed respectively. These speeds are given in terms of circuit current J and masses M_g and M_s by:

$$\frac{du_g}{dt} = \frac{1}{2}\left(\frac{F_g}{M_g}\right) J^2 \quad , \quad \frac{du_s}{dt} = \frac{1}{2}\left(\frac{F_s}{M_s}\right) J^2$$

The instantaneous values of generator gap and plasma displacement are then determined by:

$$\frac{dh}{dt} = -u_g \quad , \quad \frac{dx}{dt} = u_s \quad .$$

The following normalized variables are useful to obtain scaling relations

generator gap: $\eta = h/h_o$, closure speed: $\omega_g = u_g/u_{go}$

plasma displacement: $\alpha = x/h_o$, plasma speed: $\omega = u_s/u_{go}$

current: $j = J/J_o$, time: $\theta = u_{go}t/h_o$

The resulting differential equations are then:

$$\frac{dj}{d\theta} = \frac{(\omega_g - f\omega - r)j}{(\lambda + \eta + f\alpha)} \quad ,$$

$$\frac{d\eta}{d\theta} = -\omega_g \quad , \quad \frac{d\alpha}{d\theta} = \omega$$

$$\frac{d\omega_g}{d\theta} = -\beta j^2 \quad , \quad \frac{d\omega}{d\theta} = \frac{f}{m}\beta j^2$$

where five new dimensionless parameters occur:

$$r = \frac{R}{F_g u_{go}} \quad , \; \lambda = \frac{L_m + L_t}{L_{go}} \quad , \; \beta = \frac{1}{2}\left(\frac{L_{go}\, J_o^2}{M_g u_{go}^2}\right) , \; f = \frac{F_s}{F_g} \quad , \; m = \frac{M_s}{M_g} \quad .$$

The normalized initial conditions are for $\theta = 0$: $j = 1$, $\eta = 1$, $\omega_g = 1$, $\alpha = 0$, and $\omega = 0$. With these conditions, the plasma speed and displacement are given by

$$\omega = \frac{f}{m}(1 - \omega_g) \quad , \text{ and } \quad \alpha = \frac{f}{m}(\theta - 1 + \eta)$$

and the set of differential equations can be reduced to:

$$\frac{dj}{d\theta} = \frac{[\omega_g(1 + f^2/m) - (r + f^2/m)]j}{[(\lambda - f^2/m) + \eta(1 + f^2/m) + \theta f^2/m}$$

$$\frac{d\eta}{d\theta} = -\omega_g \quad , \quad \frac{d\omega_g}{d\theta} = -\beta j^2 \quad .$$

The system behavior thus depends on only four parameters, the normalized resistance r and static inductance λ, β = (half) the relative initial magnetic energy vs plate energy, and $P = f^2/m$, a dynamic parameter that involves the relative inductance gradient f and the relative moving conductor mass, m.

In Fig. 1, 2, 3, the results of a numerical integration of the reduced set of equations are displayed. The normalized current is observed to rise rapidly in the usual manner as the generator plates close. The kinetic energy of the plates is converted to magnetic energy and plasma kinetic energy (and also resistive heat), and the switch plasma accelerates to a significant multiple of the plate closure speed. For other sets of parameter values, the current can peak before closure is complete. (The generator plates decelerate enough for the generator impedance to become less than the sum of plasma dynamic impedance and series resistance).

Parameter surveys displayed in Figs. 4-15 provide variations of peak current and the corresponding values of efficiency (electromagnetic energy divided by total initial energy), and plasma speed. The range of normalized parameter values cover reasonable absolute values of generator and switch conditions. For example, a closure speed of 4 km/s, which is characteristic of single plate motion, with a normalized plasma speed $\omega = 17.5$, provides an actual plasma speed of 70 km/s, which is typical of experimental operation for plasma flow switching. With efficiencies in the range of 30%, a significant fraction of the generator plate kinetic energy could then be rapidly released to the implosion load.

SAMPLE SYSTEM CALCULATION

As an example of a system based on the present idealized model, suppose that two rectangular plate generators each 40 cm long by 10 cm wide are used in parallel to drive a plasma flow switch/inductive store. For a generator plate of aluminum, 3 mm thick, the plate speed will be about 4 km/s. An initial gap of 3 cm would then provide a total generator run time of about 8 μs, which should not be too long for plasma flow switch operation. The total plate kinetic energy (with only two moving plates) is 5.18 MJ. Ignoring the details of current density and field distribution in the finite (10:3) width-to-gap geometry, the initial inductance of the generator pair is about 75.4 nH.

The peak current is given by

$$J = j(\beta)\ \beta^{1/2} \left(\frac{E_{go}}{L_{go}}\right)^{1/2}$$

$$= 17 \text{ MA for } \beta = 0.05 \ (P = 1.2,\ \lambda = 0.1,\ r = .07)$$

The peak magnetic field on each plate is then about one megagauss, which is a reasonable limit for practical operation at the present level of design discussion. Note that if two-sided gap closure is employed, the generator impedance is improved but the peak field is over 2 MG, for which any improvements based on the idealized analysis would be suspect.

With the lower closure speed, the present parameters provide a plasma speed of 70 km/s and a peak magnetic energy (just prior to plasma flow switch action) of 2.16 MJ. The total circuit inductance at the time of switching is 14.8 nH, while the inductance change associated with a 10:1 radial collapse of a 4 cm long plasma shell is 18.4 nH. Ideally, the implosion kinetic energy will then be about one megajoule. System values are summarized in Table I.

The necessary initial current is $J/j(\beta) = 3.7$ MA in an initial inductance of 83 nH. This current may be obtained by using an inductive opening switch to sharpen the output of a 2.4 MJ, 20 kV capacitor bank. If the optimum inductor-to-inductor transfer is accomplished resistively, the peak bank current will be 7.6 MA prior to switching and half that value afterwards, thus providing the desired initial condition. For a constant transfer resistance value of 21 mΩ, the transfer time would be less than 2 μs and the transfer voltage would be about 160 kV. During the transfer time, plasma switch motion should require only a minor correction to the present calculations. Radiation from the plasma switch would necessitate baffling the vacuum-plastic insulator interface. The inductance of such baffling could be crowbarred out of the circuit so it does not diminish the relative change of circuit inductance during generator operation or load implosion. A major attraction of a plate-generator driven plasma flow switch/inductive store is the possiblitity of eliminating the vacuum-plastic interface between the magnetic energy store and the implosion load.

A simple extrapolation of system energies by an order of magnitude can be accomplished for the same values of normalized parameters as in Table I by increasing the number of generators by a factor of 3 and the length of each generator by 10/3. All the inductances and impedances remain about the same, so the initial plate energy of 51.6 MJ would result in 21.6 MJ of magnetic energy and a plasma implosion energy per unit length of 2-3 MJ/cm. The peak current is 54 MA, so the initial current is almost 12 MA, which would require a new source, such as a separate explosive generator (with inductive opening switch to achieve a short input risetime). An attractive alternative to six rectangular plate generators in parallel would be a single coaxial plate generator with simultaneous centerline detonation. The overall length and diameter of this generator coupled to the plasma flow switch/inductive store would be roughly 1.5 m and 0.3 m, respectively.

Table I. Summary of Sample System Values

$\beta = 0.05$, $P = 1.2$, $f = 0.02$, $m = 3.33 \times 10^{-4}$, $\lambda = 0.1$, $r = 0.07$

Assumed Generator	Derived Values	
L_{go} = 75.4 nH	Additional Inductance	= 7.5 nH
h_o = 3 cm	Allowable Resistance	= 0.7 mΩ
u_{go} = 4 km/s	Generator Runtime	= 8 μs
M_{go} = 0.65 kg	Plasma Speed	= 70 km/s
E_{go} = 5.18 MJ	Plasma Mass	= 216 mg
	Peak Magnetic Energy	= 2.16 MJ
Derived Input Bank Values	Switch Radius Ratio	= 1.29
E_B = 2.4 MJ	Switch Length	= 14.6 cm
V_B = 20 kV	Implosion Radius Ratio	= 10:1
L_1 = 83 nH	Implosion Length	= 4 cm
τ_t = 2 μs	Implosion Energy	= 1MJ
R_t = 21 mΩ	Peak Current	= 17 MA
V_t = 160 kV	Initial Current	= 3.7 MA

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3. R. S. Caird, P. J. Turchi, "Fast Explosive Flux Compression Generators for High Energy Foil Implosions," AFWL TR-222 (1972).
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5. W. L. Baker, et al, in these Proceedings.

FIGURE CAPTIONS

1. Normalized current $j = J/J_o$ vs normalized time $\theta = u_{go}t/h_o$. (Also normalized generator gap $\eta = h/h_o$).

2. Normalized plate kinetic E_g, magnetic E_m, and switch plasma kinetic energy E_s, (all relative to initial generator kinetic energy) vs normalized time $\theta = u_{go}t/h_o$.

3. Normalized switch plasma speed ω and gap closure speed ω_g (both relative to initial closure speed) vs normalized time $\theta = u_{go}t/h_o$.

4. Peak normalized current j vs dynamic parameter P ($r = 0.07$, $\lambda = 0.1$, $\beta = 0.05$).

5. Magnetic energy efficiency at peak current vs P ($r = 0.07$, $\lambda = 0.1$, $\beta = 0.05$).

6. Switch plasma speed at peak current vs P ($r = 0.07$, $\lambda = 0.1$, $\beta = 0.05$).

7. Peak normalized current j vs energy parameter β. ($P = 1.2$, $r = 0.07$, $\lambda = 0.1$).

8. Magnetic energy efficiency at peak current vs β. ($P = 1.2$, $r = 0.07$, $\lambda = 0.1$).

9. Switch plasma speed at peak current vs β. ($P = 1.2$, $r = 0.07$, $\lambda = 0.1$, $f = 0.02$).

10. Peak normalized current j vs normalized resistance r ($P = 1.2$, $\lambda = 0.1$, $\beta = 0.05$).

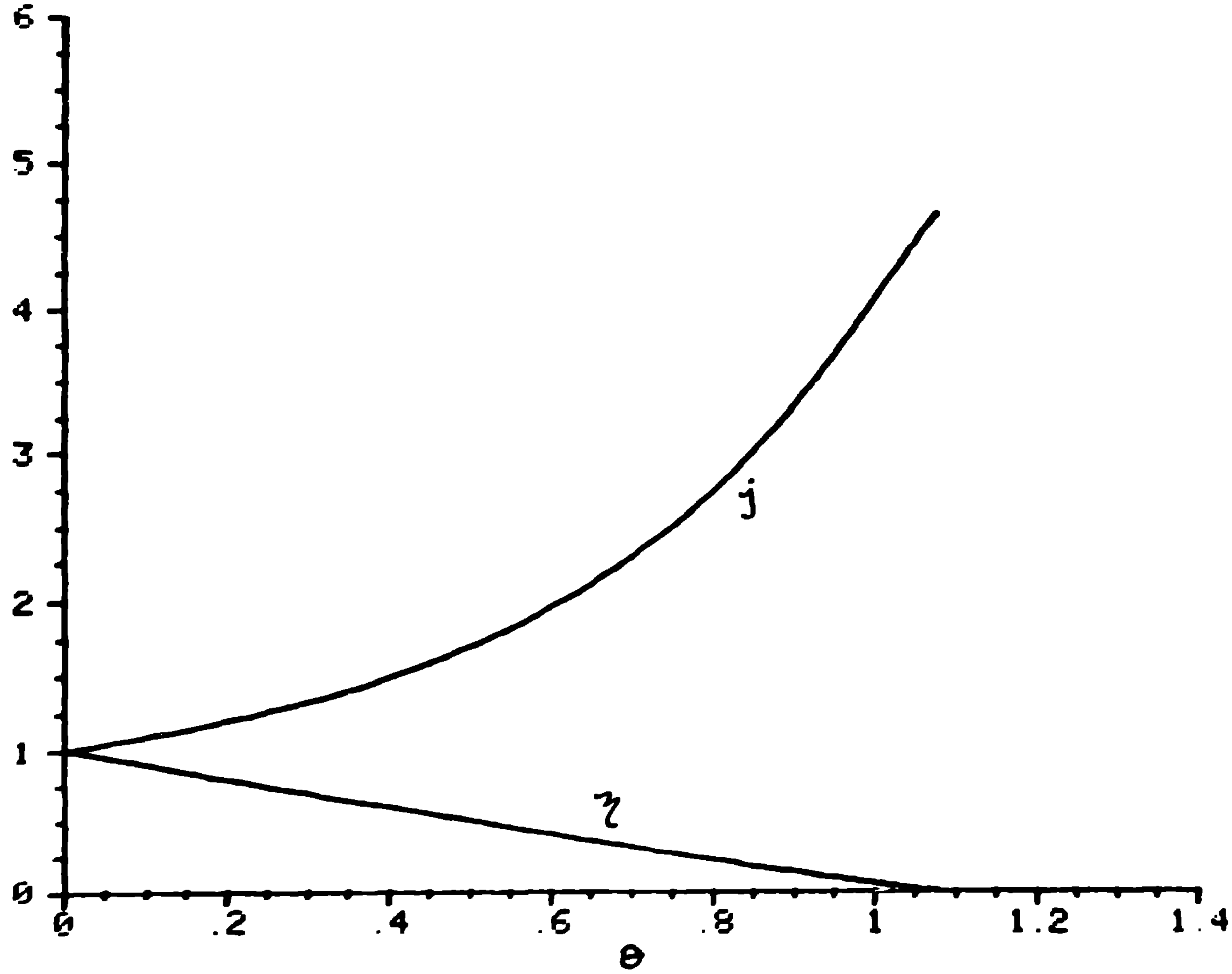
11. Magnetic energy efficiency at peak current vs r ($P = 1.2$, $\lambda = 0.1$, $\beta = 0.05$).

12. Switch plasma speed at peak current vs r ($P = 1.2$, $\lambda = 0.1$, $\beta = 0.05$, $f = 0.02$).

13. Peak normalized current j vs relative additional inductance ($P = 1.2$, $r = 0.07$, $\beta = 0.05$).

14. Magnetic energy efficiency at peak current vs ($P = 1.2$, $r = 0.07$, $\beta = 0.05$).

15. Switch plasma speed at peak current vs ($P = 1.2$, $r = 0.07$, $\beta = 0.05$, $f = 0.02$).



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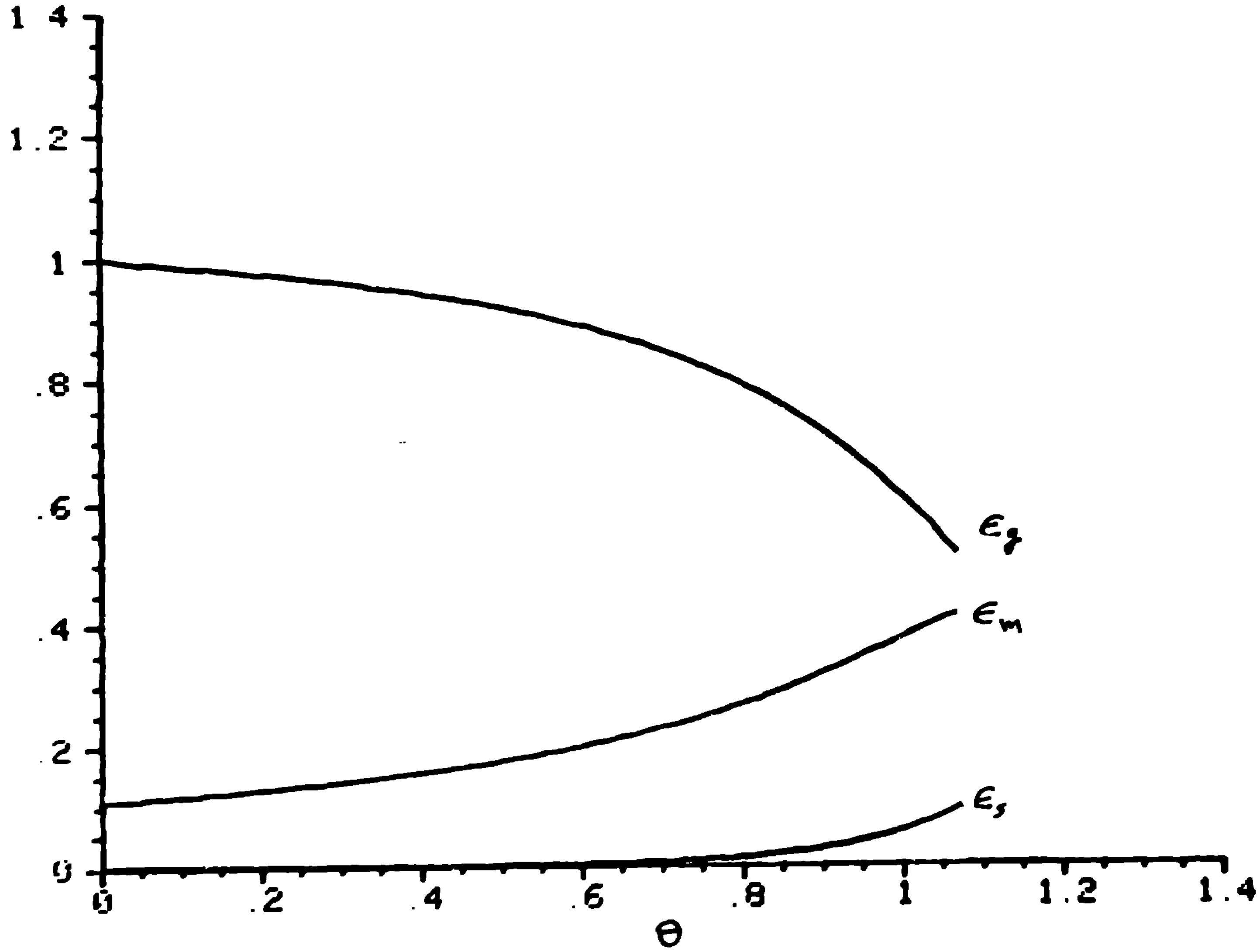

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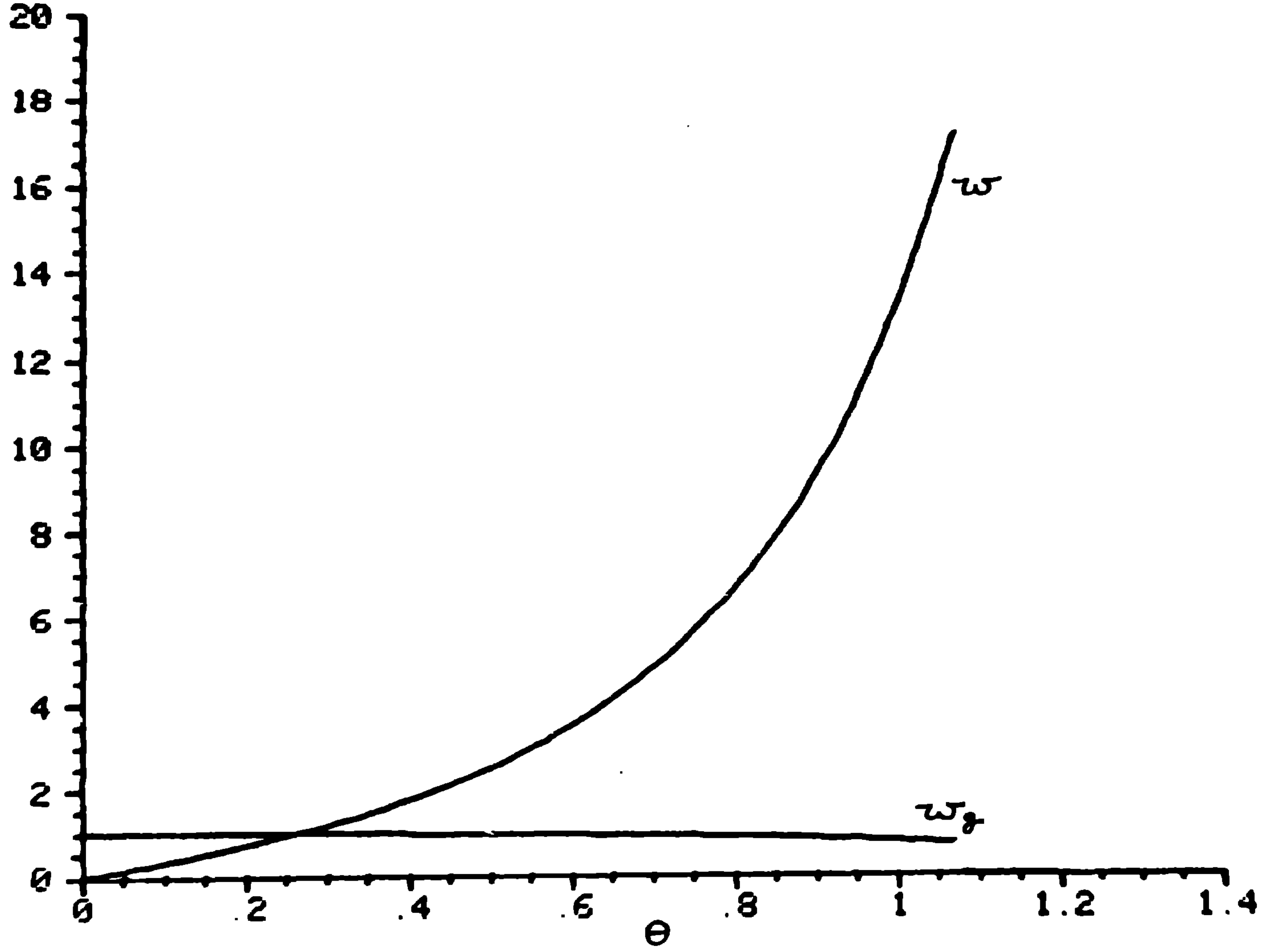

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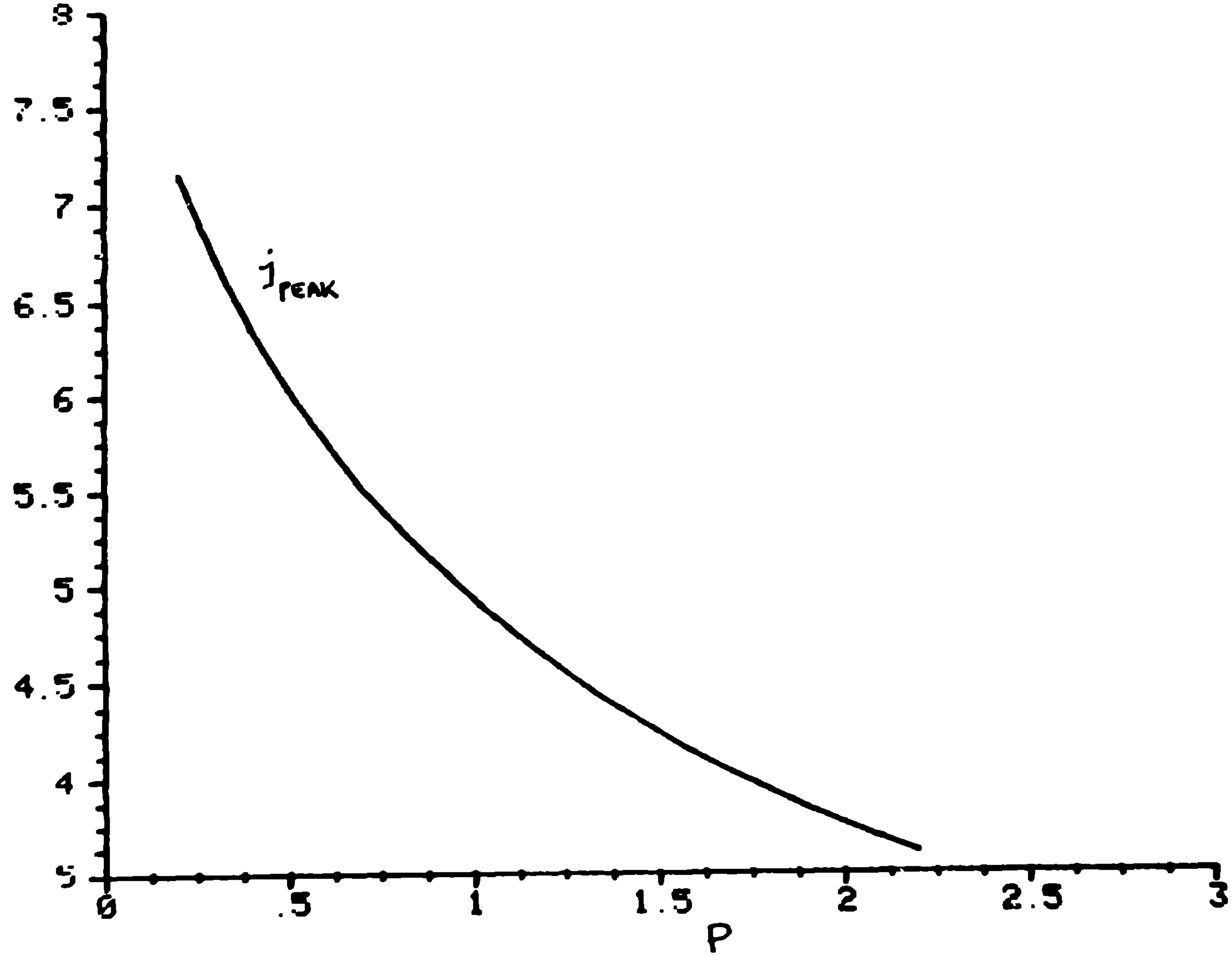

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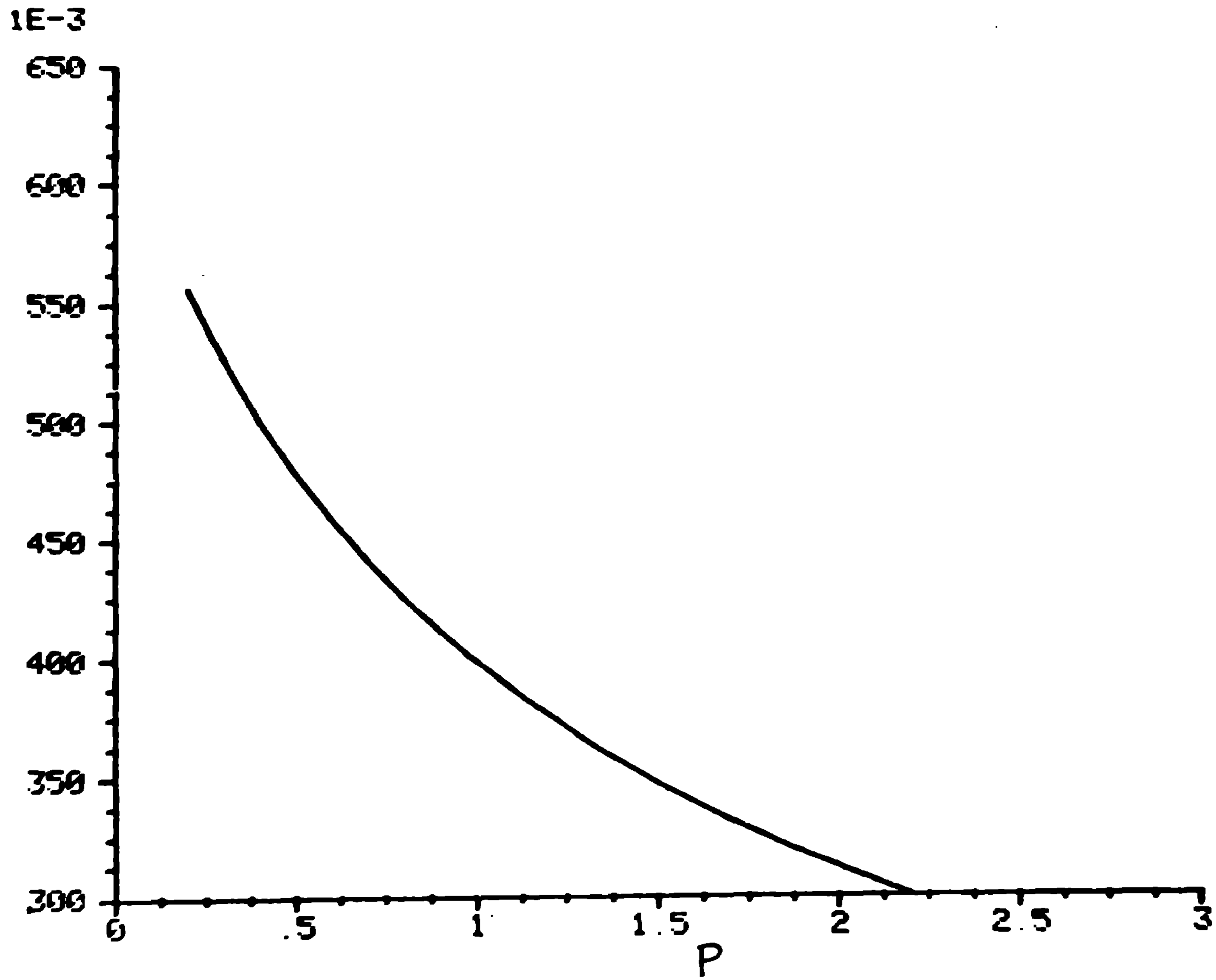
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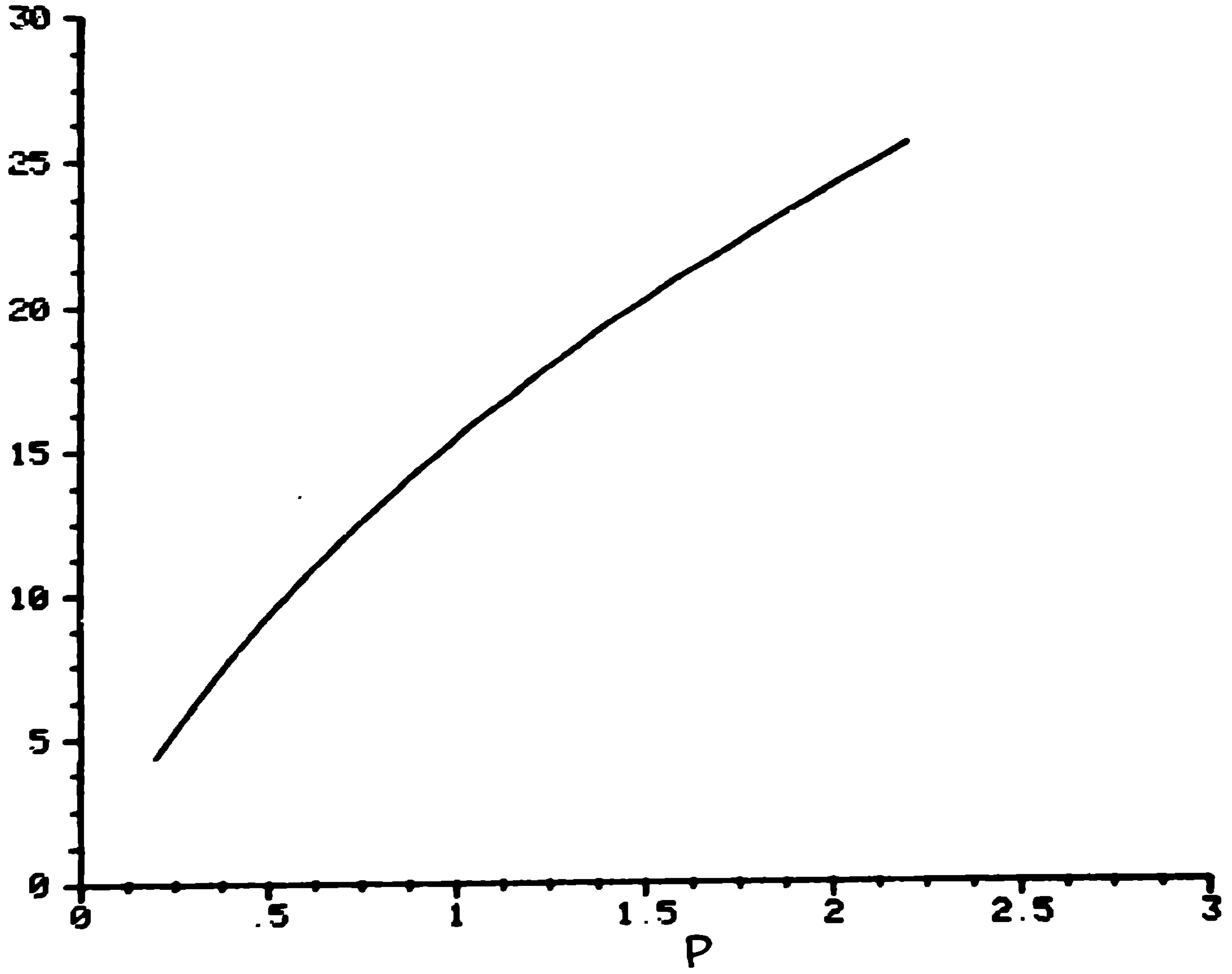
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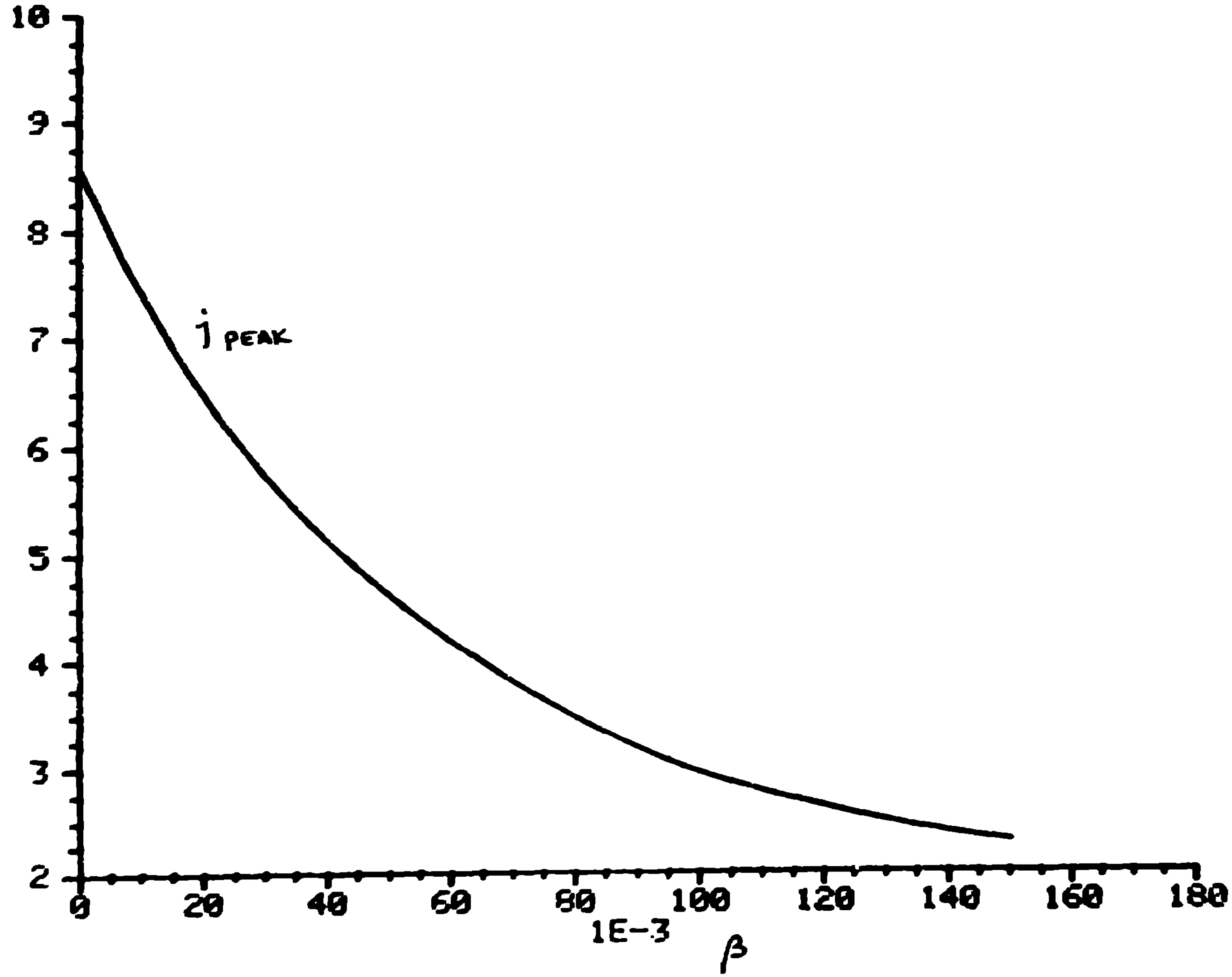
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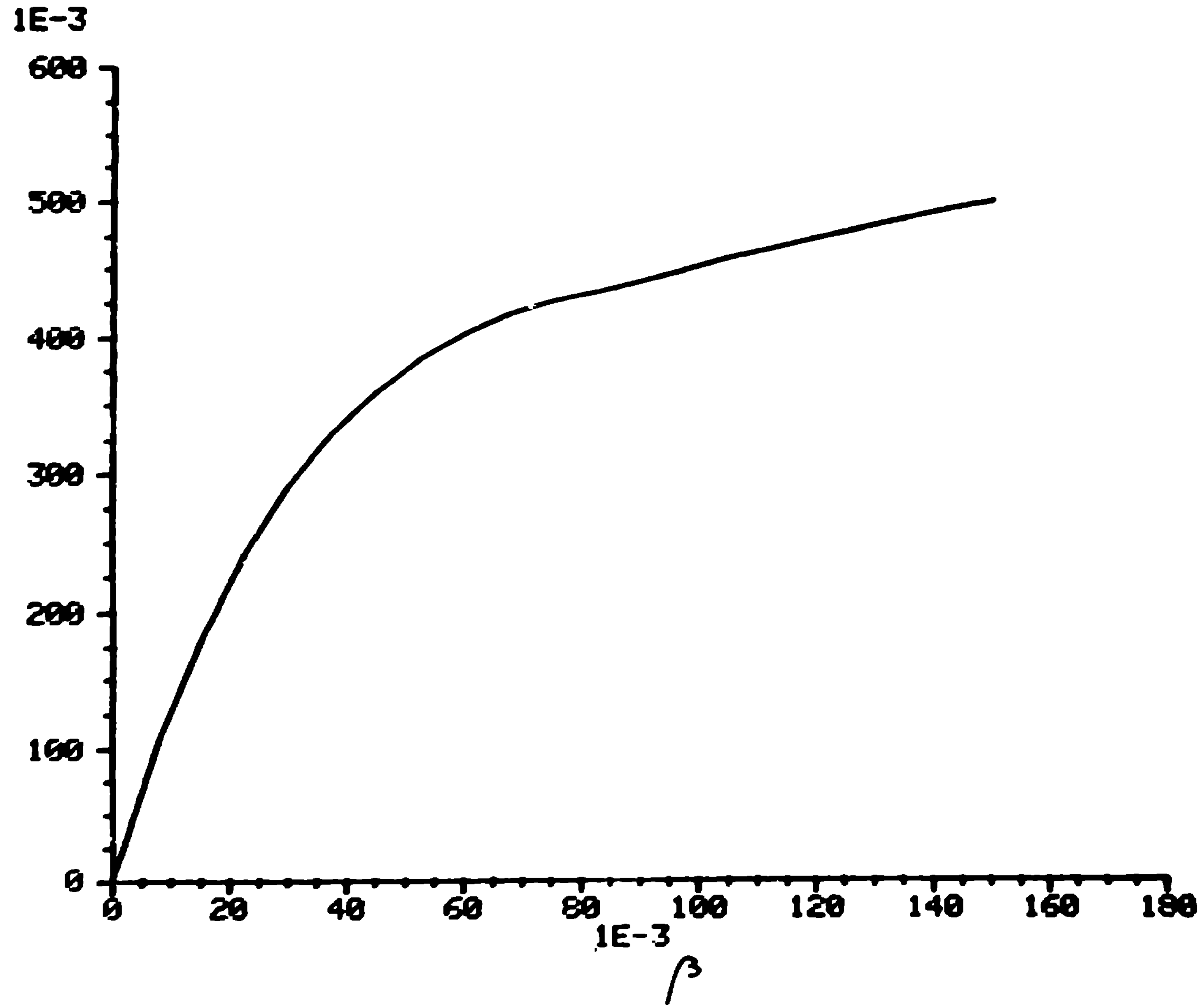

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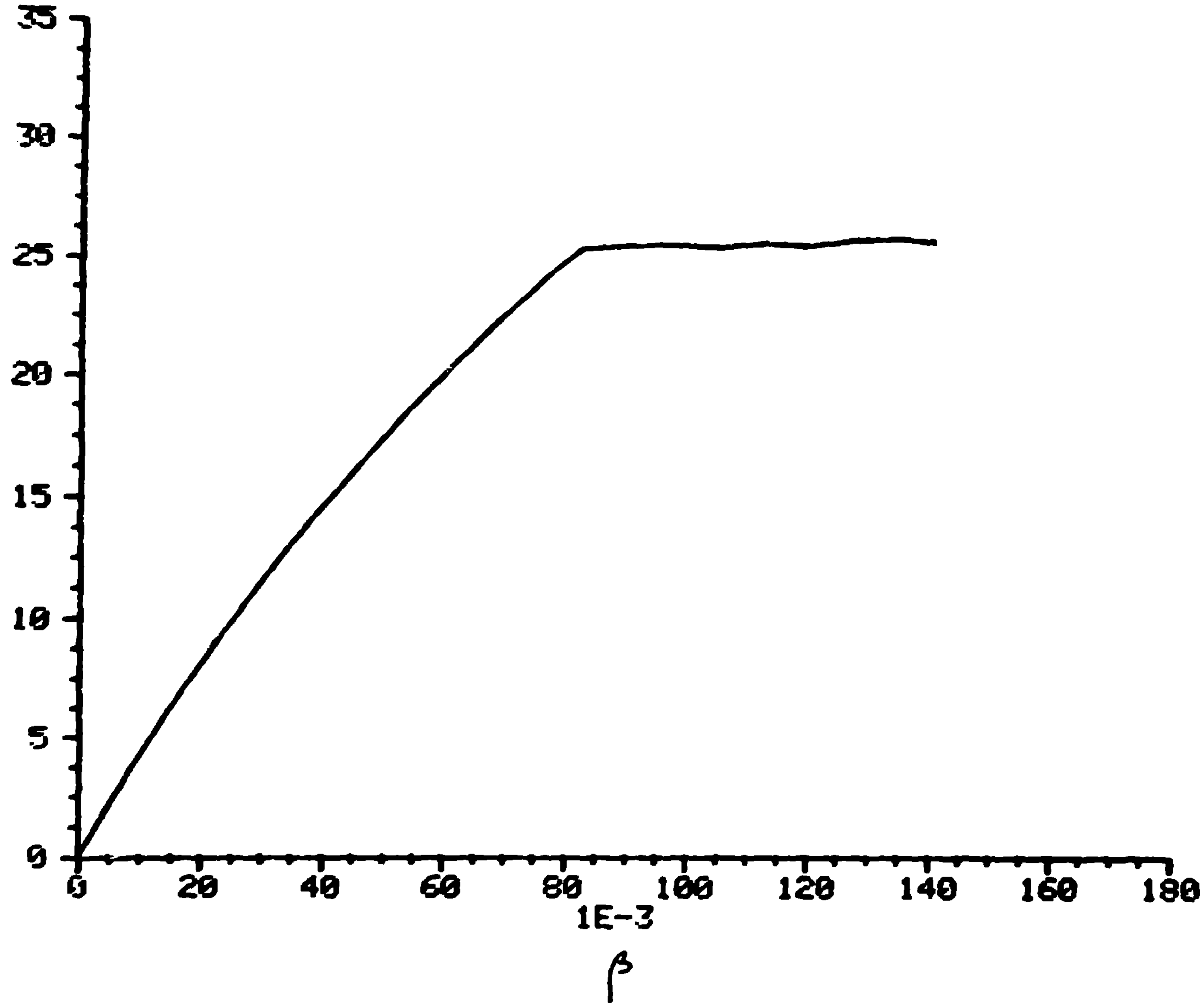
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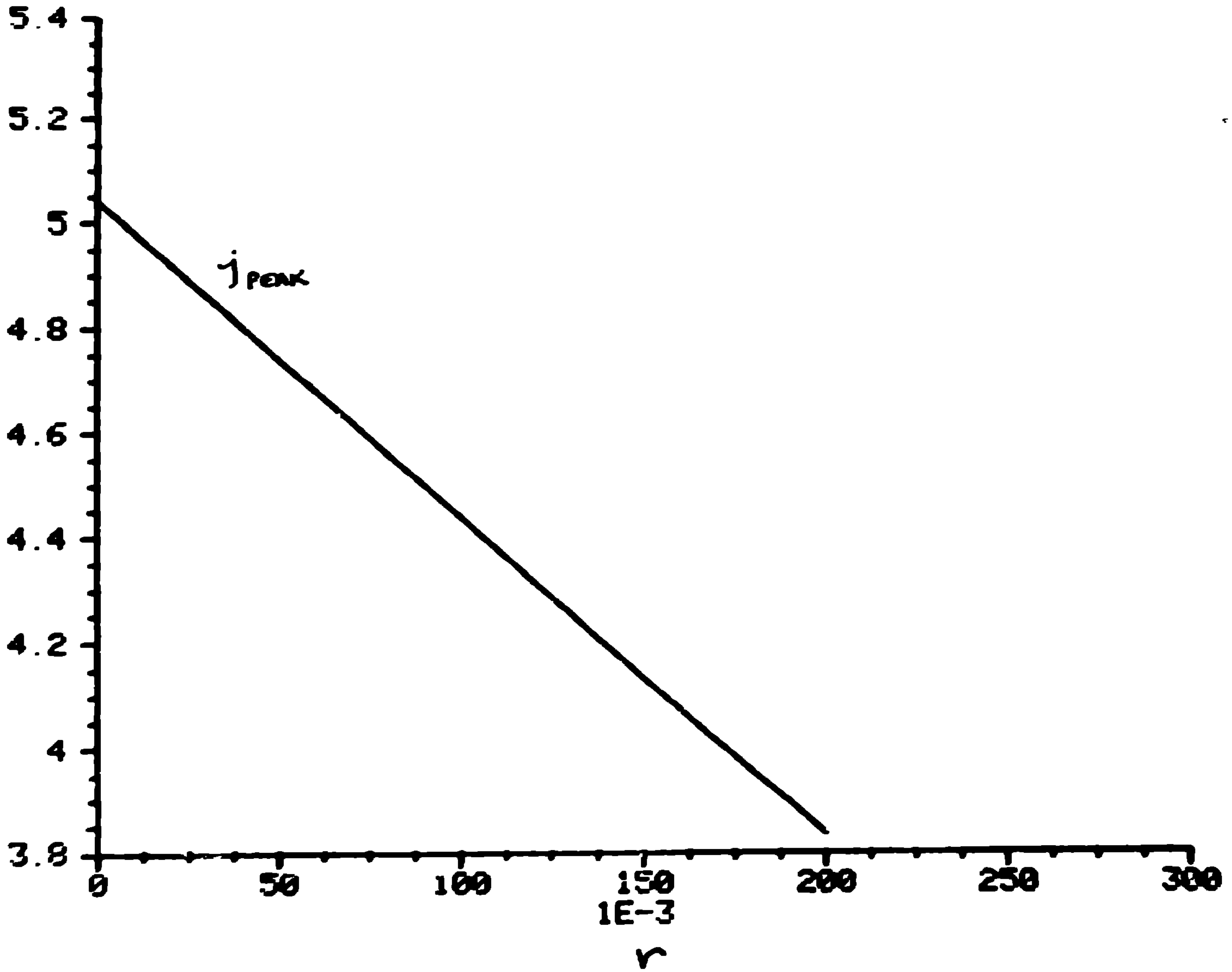
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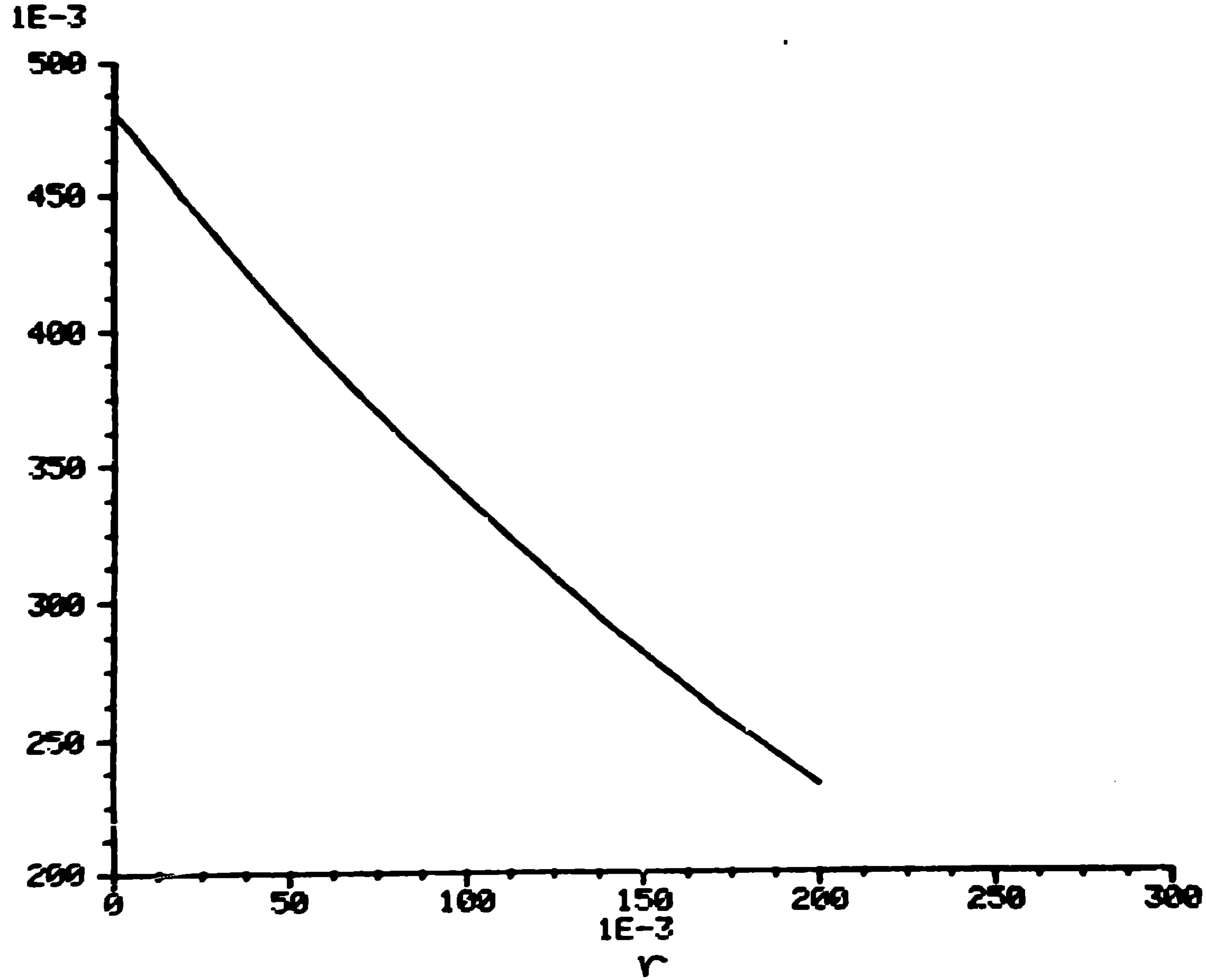
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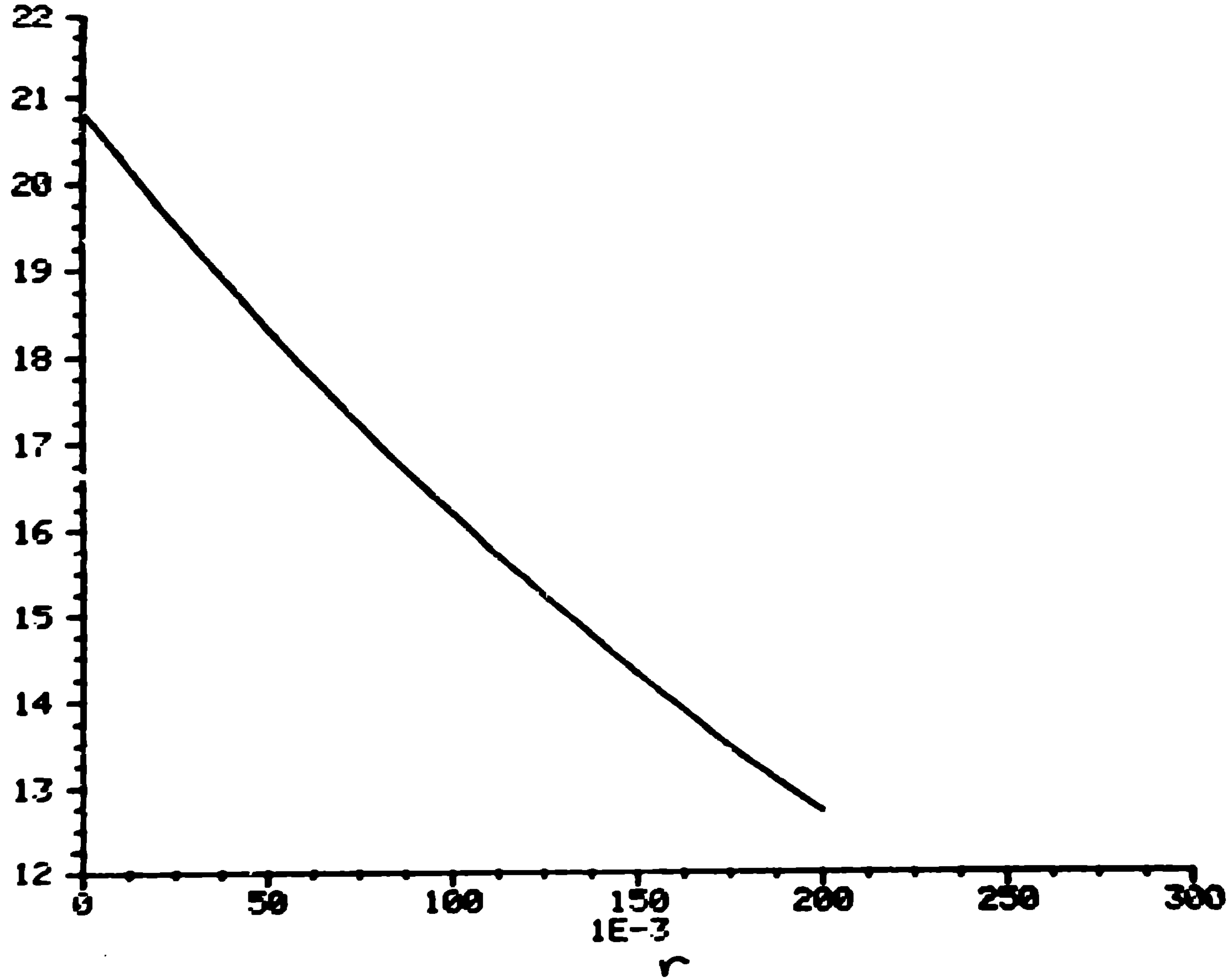

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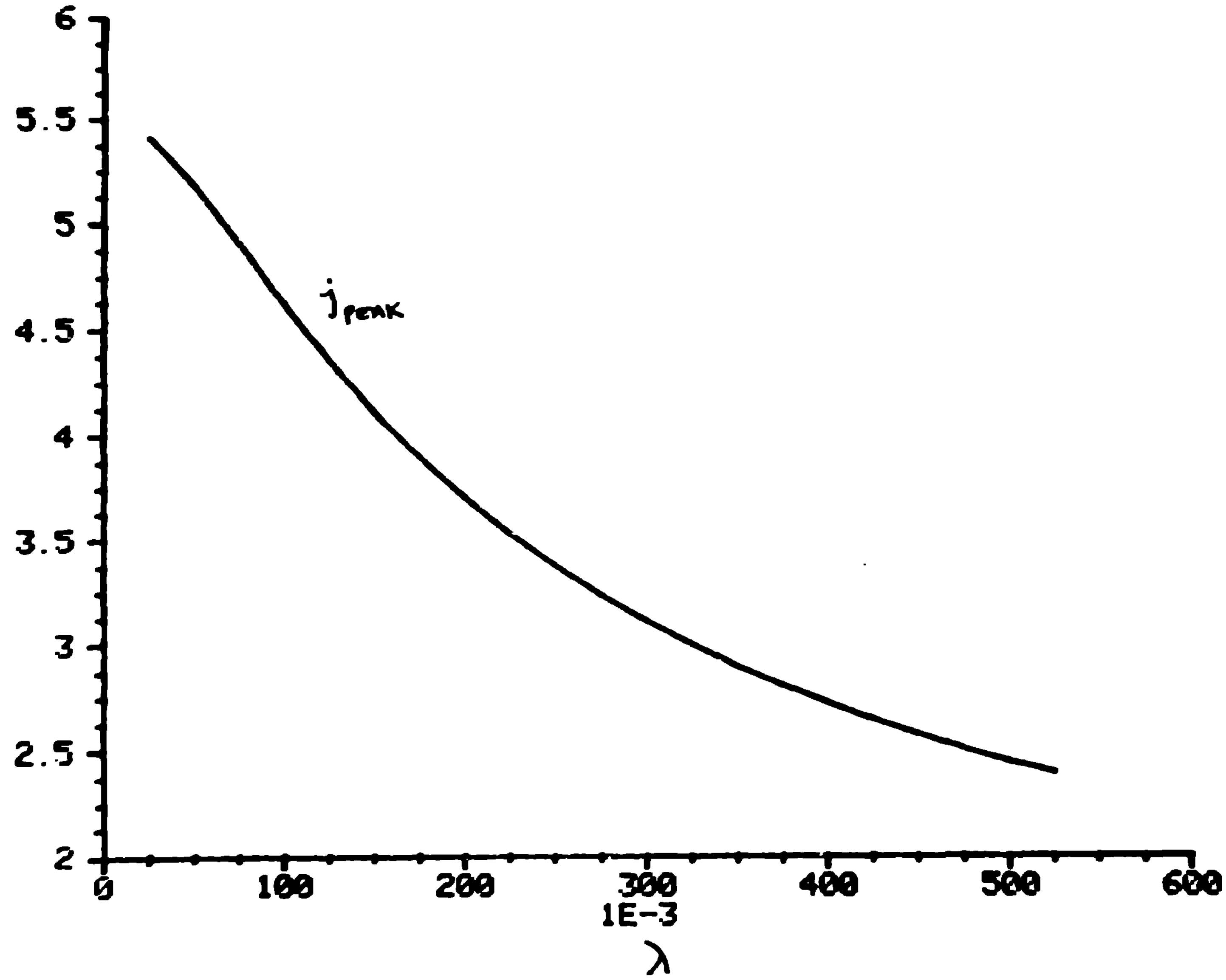

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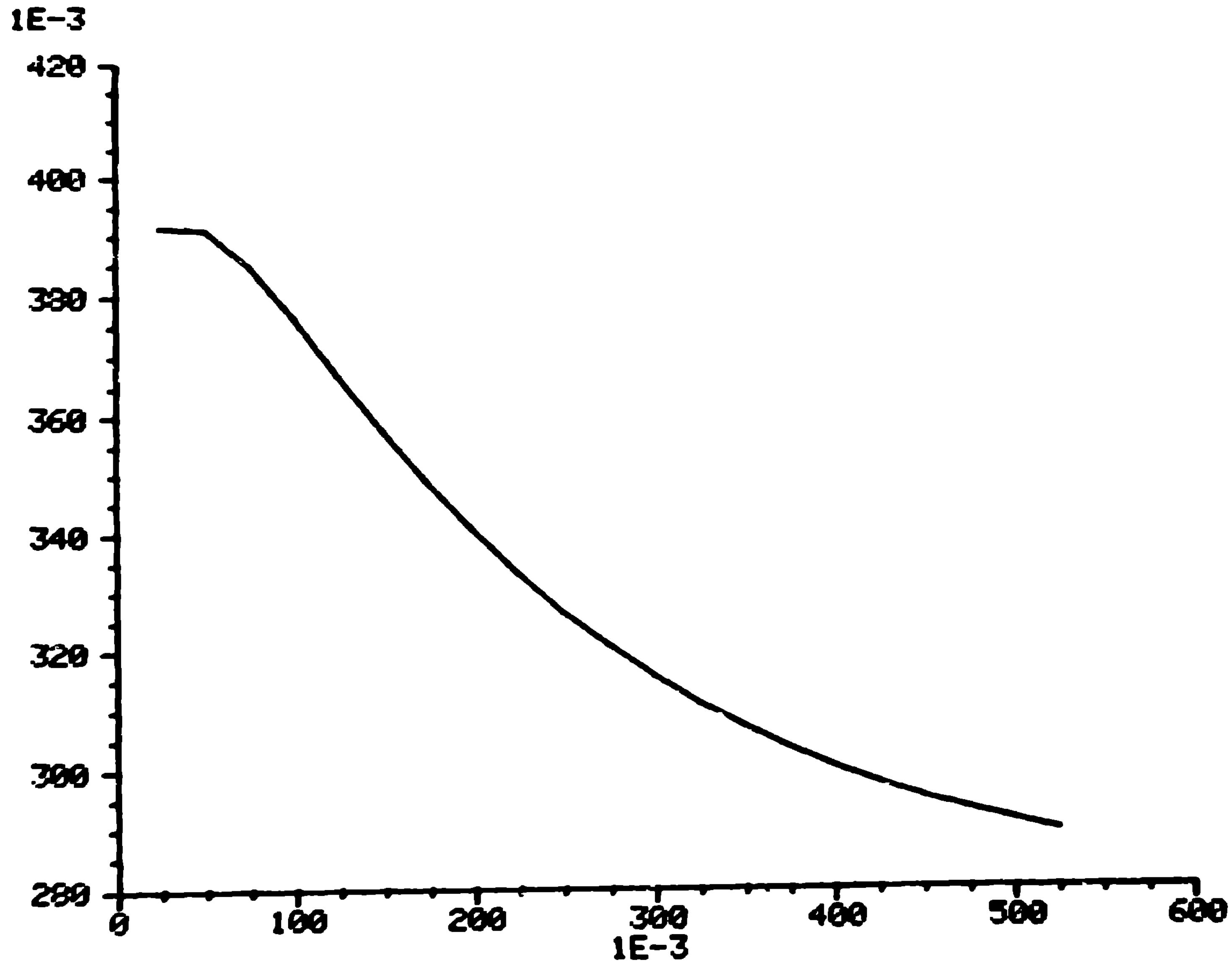
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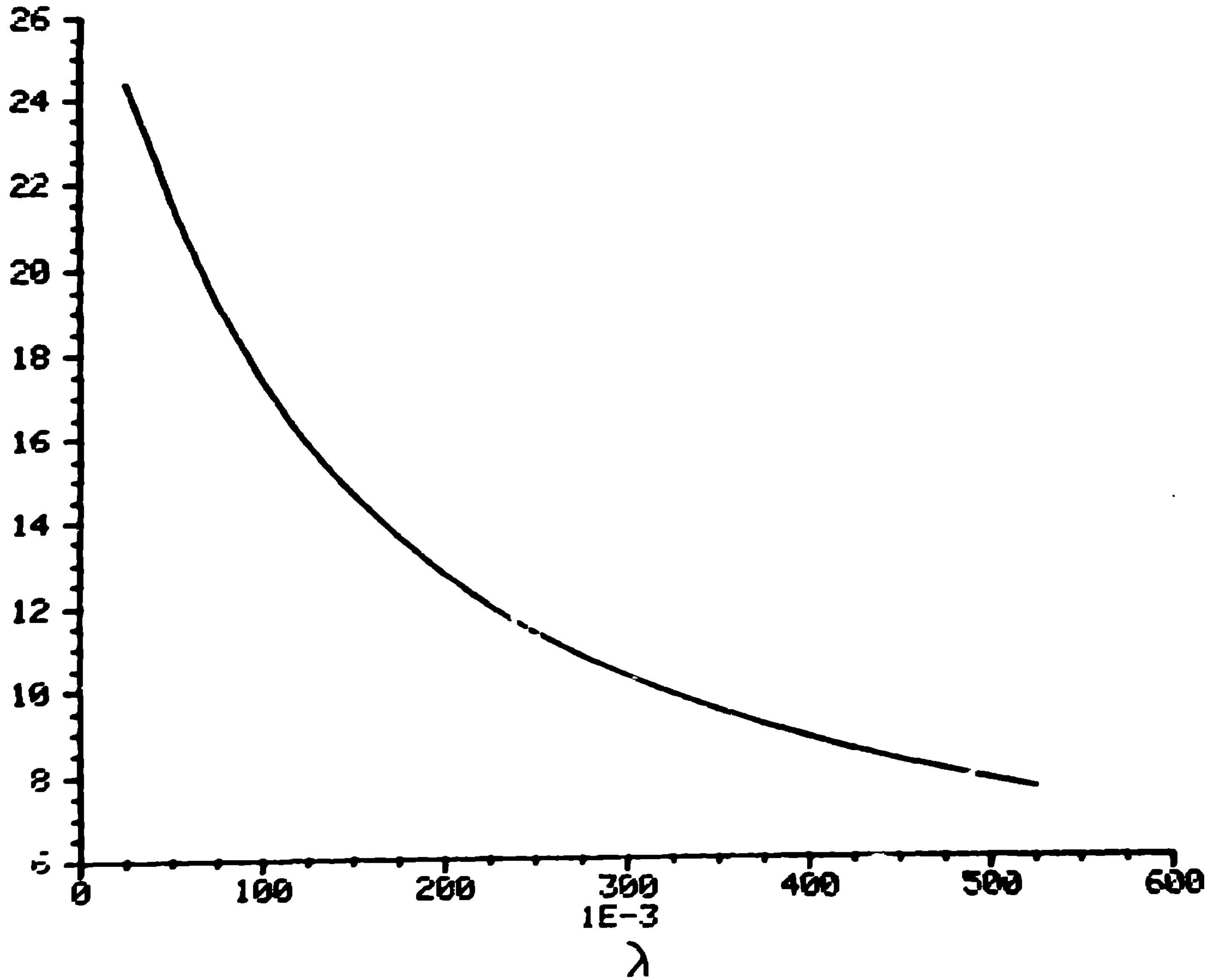
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